RAYTHEON

ELECTRONIC PROGRESS

In this issue:

ELECTRONIC PROGRESS

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RAYTHEON

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Our cover shows an exciting photograph of the championship yacht Columbia, taken during its prize-winning run in the 1958 America's Cup classic.

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Inventions

Congratulations to the following persons for their valuable contributions to Raytheon's portfolio of inventions:

Name	*Field of Invention*
Eldon W. Ball	Method of Gimballing an Antenna
Donald S. Banks	Proposed HAWK CW Radar Transmit Receive System
Donald S. Banks, William S. Murphy	Semi-Active Interferometer Fuze
Geoffrey J. Bonelle	Two New Ranging Techniques for FM/CW Radars
Robert A. Fryklund	Novel Antenna Design used on 1700 Radar
Robert A. Fryklund	Radio Navigation Aid
Mario D. Grossi	Microwave Communication System One Way Discontinuous Type, Between Railway Stations and Trains
George Lampke	Delay Line — Controlled Frequency Doubler
Charles Lindsay	Pawl Fastener
John M. Osepchuk	The "Microfier," a Converter of Microwave Power to D.C. Power
John F. Skowron, James B. Thomas	High Power Microwave Rectifier and Threshold Detector
Hugh P. Taylor	Coherent Noise Test Spectrum Analyzer
George R. Welti	High Ratio Pulse Compression System

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ELECTRONICS FOR PLEASURE BOATING

F. Lawton
Commercial Apparatus & Systems Division

This article sets the theme for the issue, electronic aids for pleasure boating. Its author is Captain Fred Lawton, sailing master of the prize-winning yacht Columbia *and Director of Marine Safety and Educational Aids at Raytheon. A master mariner with over thirty years experience at sea, Lawton has captained such famous yachts as* Vim *and* Figaro, *and sailed* Bolero *to a record for the best time ever set in the Bermuda race. Captain Lawton's work for Raytheon in promoting boating safety and encouraging the wise use of electronic navigation aids, can be viewed as a sign of the importance the industry places on this growing field of boating.*

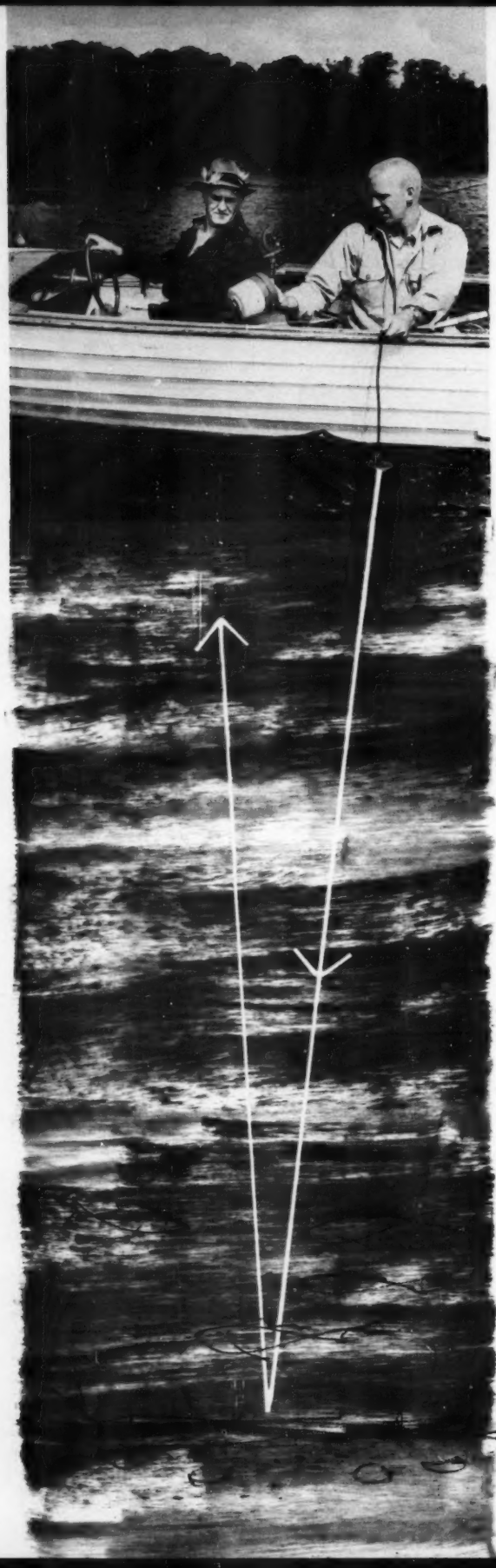
NO sport has enjoyed such a phenomenal growth as has recreational boating. A recent survey indicates that over two billion dollars were spent at the retail level during 1958 for new and used boats, engines, accessories, safety equipment, fuel, insurance, and associated items. A fair share of this money was spent for electronic devices.

The use of electronic aids afloat is not new. For years the armed services and commercial vessels have relied upon such devices to pilot their vessels in congested waters and on the open sea in all kinds of weather. With the growth of the electronics industry itself has come the adaptation of commercial and military equipment for the pleasure boat field. Modern design, new techniques, improved circuitry, smaller packaging, lower power requirements, all reflected in lower unit costs, have made electronic navigational aids available for any size boat, from an ocean liner to a row-boat.

Depth Sounders

I was first shipmates with a Fathometer® back in 1926 on the Aux. Bark "ALOHA". It was one of the early sonic depth sounders that had been perfected by the Submarine Signal Company in 1924. Today we have ultrasonic depth sounders, but the principle of operation is essentially the same, namely that of transmitting a sound through the water, measuring the time interval between outgoing and returning signal, and then presenting this information translated into feet or fathoms.

Since depth of water is of prime importance, regardless of the size of the boat, unquestionably a depth sounder is the first piece of electronic equipment the



new boat owner should consider. Along with the depth of water, information is required on the characteristics of the bottom, the location of rocks, shoals, wrecks, and schools of fish. This information is available with a depth sounder and with very little experience.

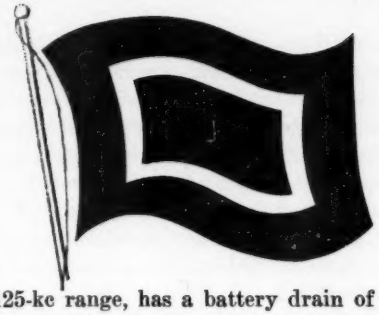
In navigating with a depth sounder, it is well to remember that exact agreement with the chart is rarely found. Such things as the state of the tide, weather conditions, accuracy of the survey of the chart, and the depth of the transducer below the water must be taken into consideration. Every attempt should be made to get a visual bearing or a radio direction finder bearing when running a "chain of soundings" in navigating. This provides you with a "fix" from which you may take your next departure. In addition, the brilliance of the light in the indicator and the width of the return signal on the recorder can tell you if the bottom is mud or rock, soft or hard.

One of the most important factors affecting the efficiency of operation of a depth sounder is the location of the transducer. This important part of the installation should be so located that the sound beam is transmitted at a right angle to the water's surface with the face of the transducer immersed in water free from any turbulence. It should also be so located with reference to the engine that it will not pick up stray electrical noises.

All depth sounders work in the same manner and consist of the same basic parts — transmitter, transducer, and receiver. They vary in the presentation of the information which may either be by a flashing red light or a recorded trace on a special graph paper or a meter indication. They may further vary according to their application in shoal, moderately deep or deep water, the frequency of the sound pulse, number of soundings per minute, voltage, power requirements, and type of transducer. In order to complete the line and to provide for the really small boat without power, there are battery-operated units such as the portable, transistorized Angler D.E. 708 powered by its self-contained mercury battery and utilizing printed circuitry. This is a shallow water depth sounder which reads from zero to 120 feet, providing soundings at a rate of 1200 per minute.

Additional shallow water units are available to suit various output power requirements; namely, the Holiday D.E. 122 for sounding from zero to 120 feet; the Holiday Mark II, D.E. 716 for depths from zero to 240 feet (both of the above are indicating types); and the Explorer, D.E. 705, a recorder providing readings from zero to 120 feet or, with a phasing kit, depths from zero to 120 feet and from 120 to 240 feet. The 7-degree sound cone at a frequency of approximately 200 kc ensures excellent definition within the limits of the equipment at all speeds.

The D.E. 706 Indicating Depth Sounder, operating



in the 125-kc range, has a battery drain of approximately 3 amps at 12 volts. This equipment may be obtained to read either in feet or in fathoms. In the model reading from zero to 360 feet, soundings are at the rate of seven per second. The deep model reads from zero to 120 fathoms with soundings at the rate of three per second, and an accuracy within 5 per cent of the indicated depth. Companion piece to the D.E. 706 is the recording-type depth sounder Model D.E. 707. This equipment, incorporating as it does all of the characteristics of the D.E. 706 Indicator, provides a permanent graph record of all the information presented by the depth sounder for future use. Largest and most flexible of the Fathometers for the pleasure boat is the D.E. 121, a recording-type depth sounder. In this unit we have a built-in power supply together with two chart-paper speeds of 12 and 30 inches per hour to permit a broader definition of bottom characteristics. A front panel switch permits a choice of four depth ranges from 0-100/90-190 feet or fathoms. The supersonic sound wave frequency used is 40 kc with a rate of either 360 soundings per minute or 60 soundings, depending upon the scale in use.

Regardless of whether one uses the depth sounder for a navigational aid on a commercial vessel or a pleasure vessel, off-shore cruising or racing, fishing or just gunk-holing, it is valuable equipment, one with which you should be familiar, and one in which you should have confidence.

Direction Finders

Of perhaps equal importance to depth of water is position, particularly when one is cruising in unfamiliar waters or during bad weather. I don't know of a more helpless feeling than to have a heavy fog bank roll in from off-shore obscuring all buoys and landmarks just as you are about to make an important landfall. This is where playing with your equipment in good weather in order to have confidence in it in bad weather really pays. This is also when time spent learning to use a direction finder is seen to have been well spent.

I often wonder just what the escorting vessel and our competitors thought of us on board the Bolero during the 1956 Bermuda Race when we confidently closed the island in a hard breeze of wind with heavy rain and visibility less than a quarter of a mile. We were using our direction finder and using it very confidently, homing on the Kindley Field radio beacon. In addition, we had our Fathometer going, checking the depth very carefully, with the result that we were able to "find" the island, stay on the outside of the shoal, finish first in the race, and break a record that had been standing since 1932. We sailed Bolero hard, yes, but the confident and co-ordinated use of the depth sounder and the direction finder helped immeasurably in our record-breaking run.

Radio direction finders for the pleasure boat field fall into two categories: the portable type, similar to the model 354 "Ranger", fully transistorized with its ferrite-bar loop; and the model 355, manufactured for Raytheon by the Apelco Division, which is designed to be permanently installed and operated from the ship's power supply.

Naturally, there are limitations to the number of refinements that can be built into a portable direction finder. On the other hand, the model 355 incorporates such features as a vertical loop, anti-noise limiter circuitry, beat frequency oscillator, sense circuitry, and in addition to permitting manual tuning in the 2-3 mc marine band, this equipment has provisions for installing 8 crystals in the receiving frequency band for monitoring marine communications.

A radio direction finder is basically a sensitive super-heterodyne radio receiver capable of receiving signals on three bands; namely, the broadcast band (550-1600 kc), the marine band (1600-5000 kc), and the beacon band (140-400 kc).

All direction finders utilize a bi-directional loop antenna to determine the line upon which the signals are being received. Regardless of the type used, the principle of operation is the same. The signal is weakest when the plane of the antenna is at right

Radio Direction Finders

angles to the signal received. It is this null, or minimum signal, which determines the direction from which the signal is being received. Angular measurement of this direction is obtained through an azimuth scale, or dummy compass card. Determination of the point at which the null is received can be audible through the use of the loudspeaker or a set of head phones, or it can be visual through the use of a sensitive null meter.

The United States Coast Guard maintains and operates radio beacon stations at strategic locations along the coast. Some of the stations operate continuously, others only during fog or other conditions of poor visibility. Within limitations, you may take bearings on any signal your set is capable of receiving. Obviously your best and most accurate bearings are those received directly over water. However, you frequently have good results with bearings taken from aviation beacons and broadcast stations, particularly those located near the water and whose signals are not deflected by any land masses.

A radio beacon signal travels a great circle track and a correction must be applied when 50 miles or more from the station. A table for correcting these bearings is found in H.O. #205, Radio Aids to Navigation, and in the Coast Pilot Books.

Sunrise-sunset effect is the distortion of a radio signal caused by the rising or lowering of the Heaviside layer in the atmosphere at this time. This causes the null to jump all over the place, in addition to which the intensity of the signal will vary from time to time.

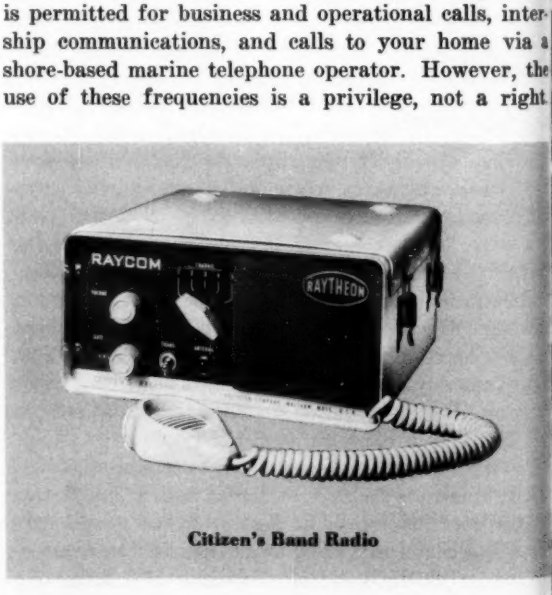
In using a direction finder, the choice of the type of bearings to be used is a matter of personal preference; however, there are a few important points to remember. Regardless of whether you take relative, true, magnetic, or compass bearings with your set, bearings on the navigational chart must be plotted in true or in magnetic. Also, the bearings that you take are the bearings of the station *from* you and must be reversed to be plotted. Finally, all bearings must be corrected for the error of the compass on the ship's heading on which the bearing is taken. Personally, I like to use relative bearings, but this is merely a matter of choice. At any rate, exercise care in correcting, regardless of the method used. This is most important.

Certainly "homing" (running with the station and its signal dead ahead) and "tracking away" are the two most familiar methods of using a direction finder. As you become familiar with your set you may use any of the equally valuable visual methods to obtain a "fix". Cross your beacon bearing with a visual bearing, or with a sounding from your Fathometer. Or, if the beacon station has synchronized signals for distance finding, take your stop watch and measure the time interval in seconds between the radio and sound signals and divide by five to find your distance off in nautical miles. In short, use all your navigational aids for the purpose for which they were designed and in an intelligent and efficient manner for your own safety and protection.

Marine Radio Telephones

As the boating industry has grown, so has the need for a rapid and efficient means of communication. The marine radio telephone was designed to fill this need. These telephones may operate in the medium frequency band of 2-22 megacycles or in the very high frequency band of 27 megacycles or 156 megacycles.

First and foremost, a marine radio telephone is safety equipment, and an installation can be justified only for this reason. Because of this and the fact that this medium of communication is governed by international agreement, we have what is known as the International Calling and Distress Frequency of 2182 kc. This is a universal, common frequency, available 24 hours a day for assistance in the event of emergency. Since it is a common frequency, it is also designated as a calling frequency which must be guarded or monitored by all vessels when underway for their own protection and for the protection of others. Fortunately, emergency calls are relatively few. In view of this, the use of the various frequencies is permitted for business and operational calls, inter-ship communications, and calls to your home via a shore-based marine telephone operator. However, the use of these frequencies is a privilege, not a right.



Citizen's Band Radio

Emergency calls have top priority and it is forbidden to use the marine frequencies in time of emergency except for associated traffic.

All marine radio telephones marketed by Raytheon are manufactured by the Apelco Division in San Francisco, California. They are available in many sizes to suit individual requirements and are within the price range of all. Package phones that come complete with an antenna, mounts, two sets of crystals, and microphones are available in such models as the RAY 11 or the RAY 19. These are 3-channel and 5-channel sets respectively, fully transistorized, type-accepted, simple to install and operate, and incorporating all modern technical refinements — an ideal telephone for the small boat with a limited cruising range. Telephones are classified in several manners. Our telephones are designated by their output; thus the RAY 11 has 11 watts output but 21 watts input to the final stage.

Since range is a function of power, for those who cruise off-shore in the larger boats the demand for greater power and increased range can be supplied with suitable equipment.

The 5-channel model RAY 23 with its 49-watt input and 23-watt output is another of the "package" sets that are available in 6 volts or 12 volts. This set comes complete with antenna, microphone, three sets of crystals. It has tunable standard broadcast and squelch with a selector-switch choice of five crystal-controlled channels in the 2-5 megacycle band for transmitting and receiving. Battery drain varies with the voltage of the set. In 6-volt operation, the model RAY 23 requires 4.5 amps when receiving and 30 amps when transmitting, as opposed to 2.5 amps for receiving with the 12-volt model and 15-amps drain transmitting.

Moving into the 2- to 6-megacycle band, we have the model RAY 41 with 6 channels and the model RAY 61 with 7 channels. These powerful telephones are great favorites with the off-shore cruising boats and the commercial sport fisherman. Both of these units incorporate provisions for remote control units which include a speaker, microphone, volume control, squelch, and channel selector switch. The RAY 41 telephone is available in 6, 12, or 32 volts, while the RAY 61 is available for operation on 12, 32, 110 V dc or 115 V ac. Both of these telephones meet FCC standards for the party boat fishing fleet which require the radio telephone to be capable of at least 25-watt output. The RAY 41 with its 65-watt input and the RAY 61 with its 100-watt input easily meet these requirements.

Output, range, number of channels, power requirements, and price all increase as the size of the set increases, but it is interesting to note that they all have one important thing in common. According to FCC regulations, every telephone licensed to be used afloat *must* contain the International Calling and Distress Frequency of 2182 kc.

There are other regulations that must be complied with. For example, the set must be licensed and have a set of call letters to be used as identification with every transmission. The captain, owner, or some other responsible person must hold at least a restricted telephone license; Part 8 of FCC Rules and Regulations must be kept on board and operators should be familiar with its text; a Log must be maintained with entries pertaining to every transmission and the fact that 2182 kc is being guarded; and it is expressly forbidden for anyone to tune or otherwise adjust the telephone, except of course by the external knobs, other than a technician holding a second-class license or better. These are sound, well thought out regulations for the protection of all.

Citizens Band

Recently, something new has been added to the radio telephone field. The FCC has authorized the use of 22 channels in the Class D, 27-megacycle Citizens Radio Band. This is a sincere effort to ease the traffic problem in the 2- to 3-megacycle band, and to supply a much needed medium of communication for use between boats working or cruising together or between a shore station and a station afloat.

This is not marine radio telephony. You do not have the common calling frequency of 2182 kc, nor do you have the range available in the 2- to 3-megacycle band. You do, however, have at hand reliable line-of-sight, relatively short-range radio communication between stations equipped with similar equipment. Over-water range of the RAYCOM Citizens Band Radio has been in the neighborhood of 25 miles, but here again, land configuration must be taken into consideration when using the equipment for shore-to-boat communication.

Radio Telephone

Gas Detector

Other Electronic Aids

The use of electronics in the pleasure boating field is not limited to radio telephones and depth sounders alone. As may be expected in an expanding industry, there will be newer applications through the development of new techniques, improved circuitry, and new components. Reduced size of equipment and lower power requirements will make radar available for much smaller boats than those presently capable of utilizing this valuable navigational aid.

Although Loran (LOng RAnge Navigation) is not manufactured by Raytheon, it probably should be mentioned here. More and more installations have been noted among the larger pleasure vessels, particularly those that cruise far off shore. Loran may be compared to an electronic stop watch whereby one measures the difference in time between signals received on a special Loran receiver. Radio signals consisting of short pulses are transmitted from a pair of shore-based transmitters. Through the use of special tables or charts, two lines can be crossed to obtain a Loran fix. Long range, high order of accuracy, and reliability in all kinds of weather make Loran a most valuable navigational aid.

In the line of small products presently available for the pleasure boat field, we have two that are very popular today. The fully-transistorized channel monitor provides the means of maintaining any one of five crystal-controlled, selector-switch-operated channels with a minimum of current drain. It can be installed in a location handy to the helmsman for easy accessibility.

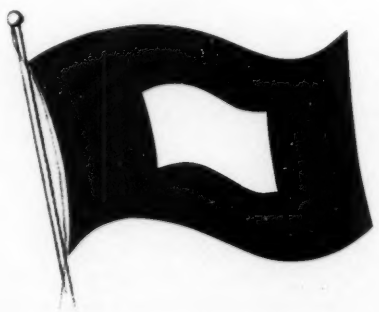
One of the smallest devices among applications of electronics, but by no means the least important, is the Model 1-384 automatic gas detector. The problem of explosion and resultant fire in gasoline-propelled vessels has always been a very serious one. Early gas detectors with temperamental bridge circuits frequently caused trouble because of bad contacts, corrosion, and drafts. Whenever it became necessary to zero the meter, one could never be sure whether this was caused by a change in the bridge circuit or fumes in the bilge. In addition, it was necessary to remove the bridge sensing unit from the bilge to test it.

The Model 1-384 automatic gas detector consists of three units: the amplifier/alarm unit, which should be mounted near the helm; the detector head, which should be mounted in a low spot in the engine compartment bilge but where there will be no chance of its being immersed in bilge water; and the interconnecting cable.

The detector head contains a platinum filament and a solar cell in a screened and baffled container. With the system "on", a limited current flows through the platinum filament in the detector head, causing the filament to glow faintly. At the same time, a "stand-by" jewel in the alarm system glows dimly. Under Safe conditions the glow, or light emission of the filament, is below the trigger threshold of the adjacent solar cell. Any gasoline fumes entering the screened detector head will burn and will cause the glow of the filament to intensify. This increase in the glow of the filament will activate the solar cell. The resultant current amplified by the transistor closes a relay and activates the flashing light circuit in the amplifier/alarm unit.

A spring-loaded "test" position of the switch is provided as a means of checking the normal functioning of the system. This merely applies a higher than normal voltage to the filament, causing the system to operate in the designed manner. In addition, this test permits "burning off" any contaminants on the filament which would tend to desensitize it, without removing the detector head from the bilge.

The increase in the use of electronic aids in the pleasure boating field today is not a passing fad. It has strong roots in the education programs of various groups and in individual desires for safer and more pleasant times afloat. Continued expansion of this market should keep pace with the growth of the boating industry itself. There is an old saying that "there are no two boats alike". We can add "Neither are they used alike, nor by the same people". It is under these circumstances that electronic equipment is being used and these are the conditions for which it should be designed — the result being flexibility, compactness, ruggedness, and dependability.



R. A. Fryklund
Commercial Apparatus & Systems Division

MODEL 1700:

A Problem in Commercial Engineering

THE design engineer in a commercial area must often establish new criteria for an equipment or system which achieved maturity in a military application. If his problem were visualized in terms of a mathematical model, one would have a system of equations with one set of solutions for the commercial application, where the variables (performance, price, etc.) are rigidly tied together; and a family of sets of solutions for the military application, where the same variables must be given a relatively wide region of existence. The transition of a design from military to commercial usage may often result in quite radical variations.

In military usage, where the performance of equipment is so crucial, design requirements come first and price must be considered a parameter which can assume more than one value, as necessity dictates. For commercial operation, on the other hand, price, as established by the market in free competition, becomes the controlling factor. The constant demand for the best equipment possible for the lowest cost affects any commercial design project to a great extent.

One such project affecting Raytheon was the design of a radar for the merchant marine. While the evolution of a new design philosophy is a fascinating story, this article can cover only the events which took place during the final stages of the development of the radar Model 1700.

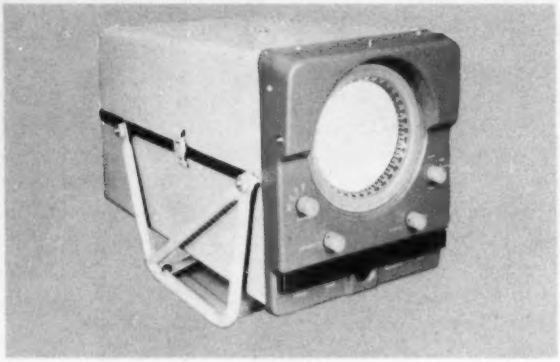
Ever since military-developed, commercially-adapted radar sets were offered to the marine market, a demand has existed for a radar to be designed specifically for the merchant marine. The old military sets were, because of cost, size, and power consumption, suitable only for larger ships, on which they were used extensively. Smaller vessels, however, needed an equipment especially tailored to their own, more restrictive requirements. As technology developed to meet the demand, less expensive radars became available. Prior to the 1700, Raytheon had a Model 1500 whose cost was approximately one-half that of all other items commonly offered on the radar market at the time of its introduction. The 1500 was a significant advance in the extension of equipment usage commercially, causing a corresponding increase in the demand for such equipment. The 1700 promises to again cut the cost of commercial radars in half, with very little sacrifice of performance or quality. For a comparison of the two radar types, see Table I.

TABLE I

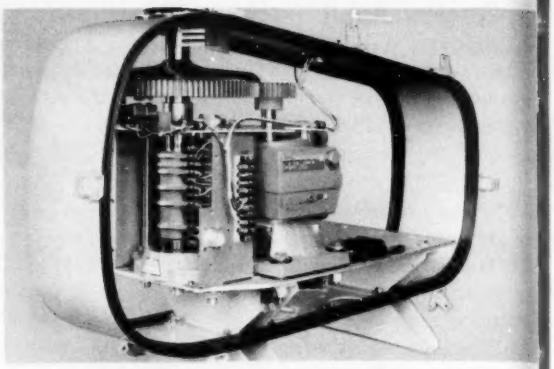
	Radar 1500	Radar 1700
Transmitter output power, peak (kw)	7½	7½
Operating frequency (mc/sec)	9345-9405	9345-9405
Antenna gain (db)	28	28.6
Receiver noise figure (db)	11	12
If bandwidth (mc/sec)	10	10
Beamwidth (degrees)	2	2
Pulse length (μsec)	0.25	0.1
Maximum range (miles)	32	12*
Minimum range (yards)	40	20
PRF (pps)	1500	2000
Display tube diameter (inches)	10	7
Price, with provision for dc input power (dollars)	4366	2195

*Based on the navigational needs of the boats using the 1700, the range has been limited by the sweep duration to only 12 miles.

The 1700 started as a study project with funding provided in a development order of long standing. The 1500, being the lowest cost Raytheon radar, provided a frame of reference. A product cost goal of one-half the Model 1500 was stipulated and the big question was formulated: "Can a radar be produced at all for this cost?" Related questions were: "Will the cost to the customer for the over-all radar function include the cost of means for converting the available ship's power to a form usable by the radar, or will the cost cover only the basic equipment, the customer



1700 Indicator



1700 Pedestal unit showing slip ring system.

bearing the power conversion costs as an extra?"; and: "Will the equipment consist of one unit or two?" Numerous conferences were held in an effort to arrive at a tentative set of specifications. Meanwhile, a study was made of typical radar systems with an eye to either eliminating entirely or reducing the cost of as many of the high cost items as possible.

A brief consideration of a possible one-unit radar brought to light an early engineering model of such a system. This was examined by all concerned, and the lack of installation flexibility was readily apparent. Consequently, a decision was made to consider only a two-unit system, even though the cost for enclosures and interconnecting cables might be increased somewhat. On the basis of this choice, the study was resumed.

This kind of engineering problem can, in general, be resolved into several areas which are largely subsystems to the over-all system. These sub-systems are fairly independent of one another, although variations in one may affect requirements of another. For this project, the sub-systems as listed were:

Antenna Systems and Related Components;

Antenna Drive and Azimuth Data Transmission Systems;

Power Conversion Systems;

Display Systems and Related Cathode Ray Tubes.

Components common to all radar systems were listed also. Each of these items may vary with regard to cost, performance, power economy, and sometimes type, but all of them are required: Power Supplies, Time Base and Sweeps, Modulator, IF and Video Amplifier, Enclosures and Chassis.

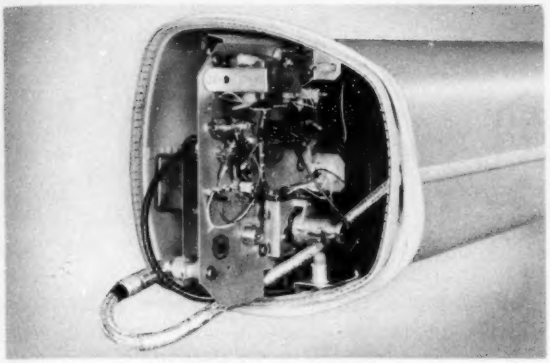
Finally, there are a number of intangible factors which should be applied as a group and which tend to modify the choice of combinations. The customer's desires are strongly reflected in this list: Dependability, Power Economy, Serviceability, Convenience of Installation, Appearance, and Durability.

It is obvious that if one functional item is taken from each of the possible variations of the above listings and these items, in turn, arranged to constitute a radar equipment, a great many combinations are possible. Some combinations, of course, will prove infeasible. Even so, there will remain a great number of workable arrangements. A few of these will have a minimum product cost and still do well when considered in the light of the many intangible factors mentioned previously.

When all of the feasible combinations are discovered and listed, a cost analysis can be made of each. Some can be eliminated immediately, if they show a gross departure from the design objectives. Others require a detailed cost study, involving vendor quotations, catalogue prices, manufacturing methods, materials and reviews of technological precedence. This is the procedure that was followed in the development of the 1700.

After the list had been "boiled down" to about five possibilities, of which the arrangement exemplified in the 1500 was one, a very close scrutiny indeed was applied to the list. At this stage, it can be seen that the intangible factors have a powerful influence on the cost, tending to drive it upward. The combination that best satisfied the over-all objectives was found and incorporated into the equipment.

The 1700 is novel not so much by virtue of any radical departures in technique as by the elimination of some old, familiar parts and rearrangement or redesign of those parts which could not be eliminated. For example, all microwave plumbing has been eliminated; there is no RF rotary joint, no waveguide sections, no elbows, and no RF coaxial power cable. The magnetron, which is a Raytheon-type 2J42, is bolted directly to the end of the transmitting slotted-array antenna. No duplexing equipment is used. There is no T-R tube and, therefore, there is no coupler, no associated high-voltage transformer and no rectifier. The receiver is bolted directly to the end of a separate receiving slotted array and uses only one crystal. The transmitter and receiver rotate with the antenna, and slip rings are used to conduct the power from the pedestal to the antenna.



1700 Antenna unit

One peculiarity of the 1700 is that it has no antenna motor per se. An extension shaft on the rotary inverter drives the gear reducer, a commercial unit which in turn drives the antenna. There are no synchros, resolvers, or other azimuth transmission devices; a low-cost synchronous motor (which also drives a cooling fan) drives the deflection coil in step with the antenna by virtue of the fact that the rotary inverter is directly coupled to the antenna and generates the 115 V ac that is supplied to the indicator.

Power supplies in the indicator have been simplified. All necessary voltage regulation is accomplished with gas tubes, eliminating hard tube regulation. No special filament windings are required and the transformer is a single, inexpensive unit supplying all positive and negative voltages.

The pulse repetition frequency (PRF) generation is accomplished by a free-running multivibrator which also supplies the voltage wave forms required in the unit.

Tuning indication, which in the past was accomplished by taking a signal from an IF amplifier, amplifying it and applying it to a meter, is now indicated on an electronic-eye type of tube which replaces an expensive meter.

The sweep circuits have been revised to an equivalent switch in series with an inductance so that natural current rise in the inductance provides a sweep on the CRT. This system easily provides a half-mile display and ranges are increased merely by adding inductance. The circuit operates with much higher efficiency than other types, is less expensive, requires no set-up, is more reliable and is independent of tube characteristics. The rotating deflection coil was redesigned to obtain a minimum product cost by eliminating plastic molding procedures and reducing the number of required assembly operations.

Extrusions and inexpensive parts have been used extensively in this design — extrusions to form the antenna and part of the pedestal enclosure, and vacuum-formed plastic parts for the antenna housing and decorative panel on the indicator. In both cases, the use of these materials has eliminated costly machine operations and tooling.

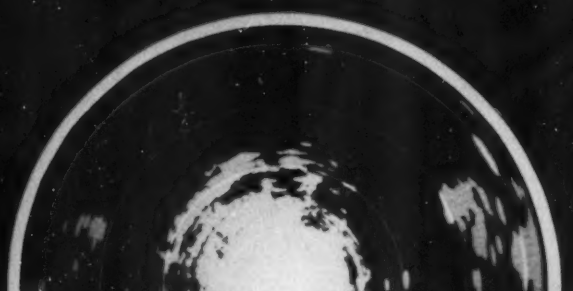
The base section of the antenna unit, which has been called the pedestal, is housed in an enclosure which uses an extrusion and two shallow, drawn pans for side covers. The extrusion in this case was designed not only to provide stiffness for the main frame of the case, but to provide a convenient means for anchorage of gaskets without cementing. The extrusions are, of course, produced in long straight bars, and are then cut to length and bent around a form, with the flanges inward, to produce the oval frame. The ends are butt-jointed with a doubler-plate which also serves as an anchor for the entrance stuffing-tubes.

Another economy measure was to design the enclosure parts symmetrically so that only one basic design is required and two pieces used. This permits larger quantity purchases, resulting in lower piece cost, as well as reduction in tooling. This was done in three places in the equipment. The antenna housing is made of two identical vacuum-formed pieces cemented together, one serving as top and one as bottom. After cementing, one end is cut off to provide access to the interior. This end is afterwards retained with a molded rubber garter-band which seals the enclosure to make it weather-tight. The two side covers of the pedestal are identical drawn aluminum pans, and the top and bottom covers of the indicator are basically identical parts.

In the interests of appearance and customer appeal, a vacuum-formed plastic panel of interesting design is provided for the front of the indicator. Here again, a cost saving was effected over the cost of the same part made of drawn or cast aluminum.

The mounting cradle of the indicator is unique. It not only provides versatility in mounting but provides easy access for servicing the indicator, once installed. The indicator can be mounted horizontally, vertically, or suspended with the same cradle. Four trunnions are provided on the indicator for attaching the cradle. The two rear ones provide a hinge action for swinging the indicator away from the mounting surface to ensure ample space for removing the covers. Once the covers are removed, all of the parts of the indicator are conveniently exposed for servicing.

The basic design philosophy behind the 1700 has proven sound in this radar's application to small work boats, fishing fleets, and larger pleasure boats; the model has had remarkable success on the market. Any further reduction of the price would require either completely radical technological changes or would result in degraded performance. The present solution, however, has proven so attractive in actual usage that it is expected to remain competitive for several years.



An Introductio

THE intended application of a pulsed radar system usually dictates the range resolution, bearing resolution, scanning rate, and range coverage of the system. In order for the radar system to detect targets within this range, the echoes from desired targets must exceed any undesired background energy. For isolated targets the background energy is generally receiver noise, but for airplane targets the undesired background energy may be ground reflections occurring at the same range and azimuth as the airplane.

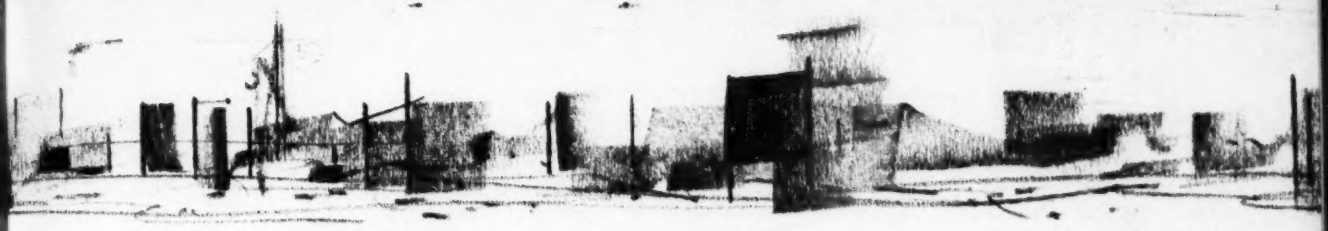
In the isolated target case, the requirement is to maximize the total echo energy received from the target so that it can compete with receiver noise. This means high average transmitted power, which leads toward a long pulse length and a high pulse repetition frequency (PRF). In general, however, the pulse length must be short enough to provide resolution between targets separated by some reasonably small difference in range, and the PRF must be low enough to allow time for the echoes from distant targets to return to the radar between pulses.

Clutter

Because of the earth's curvature, the radar antenna must look near the horizon to see distant airplanes. Consequently, strong reflections are also received from ground targets such as hills, buildings, and water towers, especially at distances up to 50 miles. These fixed targets are often called "clutter" because their echoes tend to clutter a PPI (Plan Position Indicator) presentation and prevent airplane echoes from being seen. For air traffic control or air defense purposes, it is very desirable to display on the PPI only the airplane echoes and not those of clutter. Furthermore, to permit tracking airplanes over areas containing clutter, the radar system must display an airplane echo even when it is received at the same time as a stronger echo from clutter. The problem is thus one of detecting airplane targets in the presence of an undesired background of ground reflections. In this case, higher power is of no advantage since both the desired signal and the ground reflections are increased in proportion. Contrast is aided by maximizing resolution, such as by using a sharp antenna pattern and a short pulse length, but these techniques are limited by other system requirements. What is needed is an approach

to MTI System Design

T. A. Weil
Equipment Division



that utilizes some characteristic of the desired targets that distinguishes them from the competing ground reflections. One such characteristic is motion. Techniques have therefore been developed that will reject fixed target echoes and yet maintain high sensitivity to echoes from moving targets. Such systems are called Moving Target Indicator (MTI) systems.

Amplitude Comparison MTI

How can we tell which targets are moving? Since a pulse radar measures target range accurately, we can check to see if the range of a target is changing. A delay line can be used to remember or "store" the video echoes from one transmitted pulse for comparison with the next set of echoes. However, in a typical intrapulse interval of 1/360th of a second, an airplane flying at 300 mph moves only 15 inches and the time of its echo return will change by only 0.0025 microsecond, or about a thousandth of a pulse length, which is far too small to notice. Making the comparison during the whole time the antenna is looking at the target — typically 0.036 second or 13 pulses — doesn't help much. In the quick glance the antenna gets at any target, an airplane doesn't move enough to be distinguishable from a fixed target using this method. Either we must take a longer look or we must find some finer scale against which to measure target motion.

Scan-to-Scan MTI

A longer look can be taken by comparing target positions from scan to scan instead of from pulse to pulse. A scan-to-scan memory has to be capable of storing a tremendous amount of data on range, azimuth, and amplitude of all targets. The best attempts to do this to date have used storage tubes as the memory and have been able to eliminate fixed targets well. However, the system is expensive, and its limited resolution causes moderate speed targets also to be eliminated. Furthermore, some auxiliary system (such as noncoherent MTI, described later) must be used to see airplanes flying over fixed targets. A scan-to-scan MTI system does have the advantage that it can notice motion in azimuth as well as in range, and some day an excellent scan-to-scan MTI system may be made using a computer type of memory. Such a system is also free of blind speeds, which will be discussed later.

Coherent MTI

Fortunately, a finer scale than pulse length is available against which to measure target motion, and that is the radio frequency (RF) wavelength λ. The phase angle of the echo RF return can be measured, and a change in target range of an eighth of a wavelength (a change in round-trip distance of a quarter wavelength) will cause the resultant signal to go from zero to maximum while fixed targets will always produce an unchanging output. Here then is an extremely sensitive scale that will show a large change in output for a target motion between successive pulses of about an inch, or a change in echo return time of 0.0002 microsecond, which is a ten-thousandth of a pulse length! Measurement of RF phase requires a reference signal source against which to compare the echoes, and this source must bear a consistent relationship to the pulsed transmitter signal. MTI systems that measure the phase information in the echoes are therefore known as "Coherent" MTI systems. It will be seen later that moving targets cause the train of pulses out of the phase detector to vary at the target doppler frequency, so the term "Pulse-Doppler" MTI is sometimes used instead. The target doppler frequency is $2V_r/\lambda$, where V_r is the radial component of target velocity.

Noncoherent MTI

Oddly enough, a type of performance that is in some ways similar to Coherent MTI can also be obtained from an Amplitude Comparison MTI system. As noted above, an Amplitude Comparison system does a poor job of distinguishing a moving target from a fixed target. In the special case, however, where a moving target echo and a fixed target echo are received simultaneously, these two RF echoes add vectorially and the amplitude of the resulting video output then depends on the phase relationship between the two echoes. Between successive pulses, the phase relationship between the fixed and moving target echoes will change at the same rate that the moving target echo phase would change in a Coherent MTI system and the video output amplitude will vary accordingly. A video amplitude comparison system between successive echo returns will then give a usable output for a moving target in the presence of a fixed target, even

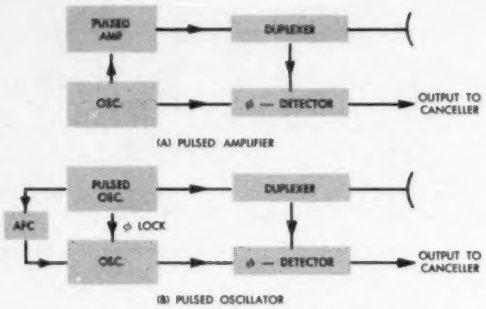


Figure 1

though this system gives no output for a fixed target alone or for a moving target alone. Since this system depends on the moving target echo return "beating" with a fixed target echo instead of with an independent coherent reference signal, this system is more commonly called "Noncoherent MTI". This system by itself is of limited usefulness because of its inability to see a moving target alone but is sometimes used in conjunction with other techniques.

Coherent MTI Systems

We will now examine in detail how a modern coherent MTI system extracts its information from the received signals. Coherent systems are now the most common type, and further discussion will be limited to such systems. These systems are basically as shown in Figure 1.

Pulsed Amplifier System

In the first system shown, the transmitted pulse consists of an amplified sample of the continuously running reference oscillator. The output of the phase detector will be a pulse at the time when the echo signal is received; and the amplitude of the pulse will depend on the exact phase angle of the reference oscillator at which the echo signal begins to arrive at the receiver. This system thus measures the time required for an echo to be received, in terms of cycles of the reference oscillator, but it indicates only the fractional part of a cycle beyond an integral number of cycles, rather than the total of both. The phase detector output would change from zero to maximum, for example, if the target moved a distance of an eighth of a wavelength toward or away from the radar; how this information is used will be shown later. It can be seen that this system is extremely sensitive to target motion, but it is therefore also very sensitive to any accidental variations taking place within the radar system.

Pulsed Oscillator System

The second system shown in Figure 1 is actually much more common. Here another oscillator such as a magnetron is pulsed to produce the transmitter signal. In order for the phase information in the echo to be significant, this pulsed oscillator must bear a known phase relationship to the reference oscillator against which the echo will be compared. To insure this, the frequency of the reference oscillator is automatically controlled to be as close as possible to the frequency of the pulsed oscillator, and then the reference oscillator is phase-locked to the pulsed oscillator each time the transmitted pulse is produced. The result is then closely the same as if a sample of the reference oscillator had been amplified and transmitted.

Stalo, Coho

In practice, superheterodyne systems are more commonly used because they can be made more sensitive and more stable than a reference oscillator at RF. The two basic systems just described are actually used as superheterodyne systems, as shown in Figure 2. The Stalo is a stable local oscillator which, via the mixers, converts signals from RF to IF or vice versa. The Coho is a coherent (or reference) oscillator at IF which, together with the Stalo, provides the reference frequency. It is in terms of this frequency that the echo returns are measured. In the pulsed oscillator system, the Automatic Frequency Control (AFC) is applied to the Stalo and the phase-locking is more suitably applied to the Coho.

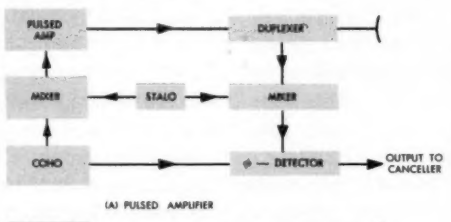


Figure 2

Raytheon's ARSR-1A "Flight Tracker" radar is an example of this type of coherent MTI system. Table I lists the parameters of this system; these characteristics provide a range of 185 miles on a T33 jet trainer and well over 200 miles on larger targets. This system is shown in Figure 3.

Phase Detector

We may now look at the phase detector characteristic, as shown in Figure 4. The output of the phase detector depends on the phase angle between the reference signal and the received signal, as shown; it is convenient to think of vector diagrams as also shown,

Figure 3

TABLE I	
PRF	360 pps
Pulse length	2 microseconds
Peak power	4 megawatts
Antenna azimuth beamwidth	1.3 degrees
Antenna gain	34 db
Antenna rotation speed	6 rpm
Transmitter frequency (tunable)	1280-1350 megacycles
Scanning time per beamwidth ("time on target")	0.036 second

in which the phase detector output depends on the amplitude of the received signal vector component that lies along the reference vector. Three cases are shown: a strong fixed target, a moving target, and both together (occurring at the same range). The successive pulses out of the phase detector in each case will be as shown. Since the phase detector output can be positive or negative, the video information at this point is commonly called "bipolar video". In cases where a moving target is present, the phase detector output varies at the doppler frequency rate, as determined by the number of cycles of the reference oscillator by which the echo return time changes per second. The purpose of MTI is not only to reject fixed targets and accept moving targets, but also to detect relatively weak moving targets in the presence of strong fixed targets that may occur at the same range, such as when an airplane flies over a city. However, any instabilities in the radar system will modulate the phase angle of strong fixed targets exactly as if a moving target were also present, and the receiver may think that a moving target is present even when one is not.

Canceller

To extract the moving target information from the phase detector and reject fixed targets, the output of the phase detector is fed to a unit called a canceller, in which steady values of phase detector output at any range are cancelled out and the variations are retained. This is normally done by subtracting the successive phase detector outputs that result from successive transmitted pulses. A delay line is normally used to store the information from pulse to pulse, and more than one delay line can be used to permit comparison of more than two pulse periods. The bipolar output of the comparison circuit is then rectified for presentation on the PPI as MTI video.

In the absence of a moving target, the amount of residual variation in the canceller output, left after cancellation of strong clutter, is called the "residue". If the residue is 40 db smaller than the maximum signal output, then this is called 40-db "cancellation ratio". This also means that a moving target, in the presence of a 40-db stronger fixed target, would produce no more output from the canceller than strong clutter alone. In order for the system to detect a moving target in the presence of strong clutter, however, the moving target must over-ride the residue from clutter by some noticeable amount, in the same way that an ordinary signal must over-ride receiver noise level to be detectable with sufficient certainty. The measurement, at the receiver RF input, of the ratio of the strength of this barely discernible moving target to the strength of the fixed target that is being cancelled has come to be called "sub-clutter visibility" or simply "SCV", and is the true measure of performance of an MTI system. Instabilities in the radar system will not interfere with the detection of a moving target by itself but, by limiting the cancellation of clutter, instabilities may prevent the system from being able to see a weak moving target in the presence of clutter.

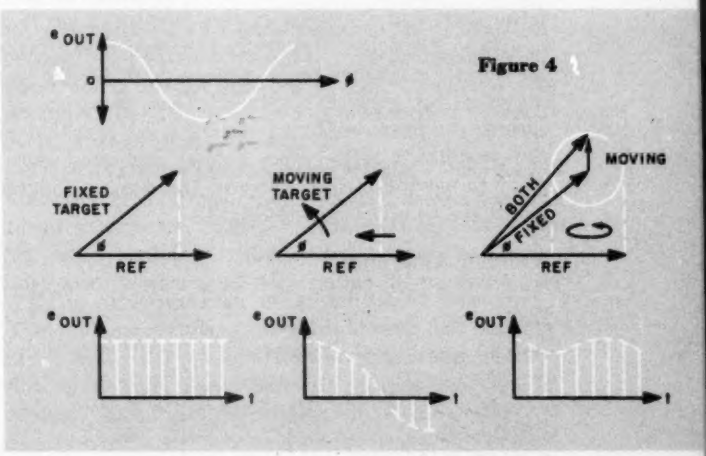
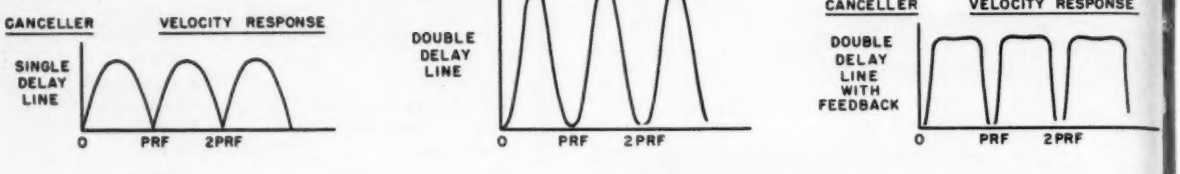


Figure 4

Figure 5



Blind Speeds

It has been seen that the phase detector output for a moving target is a train of pulses at the radar PRF, modulated in amplitude at the doppler frequency corresponding to the radial component of target velocity. If the target is flying a course such that its radial velocity is zero, its echo will be cancelled just as if it were a fixed target. Furthermore, at particular values of the radial component of velocity that give doppler frequencies equal to the PRF or its harmonics, the phase detector output pulses will be constant because the target moves exactly one or more wavelengths between pulses, and the echo will again be cancelled as if it were a fixed target. At these speeds the MTI system is said to be "blind" to the target, and these speeds are called the "blind speeds" of the system. For the ARSR-1A, blind speeds occur at multiples of 92 miles per hour.

In effect, a coherent MTI pulse radar takes samples, at the PRF, of the target doppler frequency. Blind speeds would not occur if the doppler frequency were measured continuously, such as with a pure CW radar, but then range information would be lost. One solution to the problem, at the cost of complexity, is to sample the target doppler frequency at a non-uniform rate by "staggering" the PRF. In this fashion an MTI system can be made so that no doppler frequency within the range of interest will be lost completely, but there may be wide variations in sensitivity.

Velocity Response

Between its blind speeds, any MTI system will respond with varying sensitivity to different doppler frequencies and the shape of this sensitivity curve is called the "velocity response" of the canceller. Typical velocity responses for single and double delay line cancellers are given in Figure 5. These responses are various compromises aimed toward good rejection of scan-modulated clutter (see below) and good sensitivity to moving targets. Any of the response curves shown can be selected in the ARSR-1A.

Scanning Limitation

In order to set limits on instabilities in an MTI system, the desired over-all performance, or SCV, must be established. Unfortunately, the ability of an MTI system to cancel fixed targets is limited not only by instabilities in the system but also by the modulation of the phase detector output from fixed targets as the antenna scans past them. In effect, scanning modulation tends to make fixed targets look like slowly moving targets that are not as well rejected by the canceller. The antenna rotation speed is set as low as possible to minimize this effect, but several rpm is about the slowest that will permit an operator to track fast airplanes reliably. How serious the effect of scanning modulation is depends on the shape of the velocity response of the canceller being used, but the useful cancellation ratio is generally limited by this factor in conventional MTI systems to around 20 to 30 db. If this value of cancellation ratio is to be realized, the rest of the system must be designed to be somewhat better than this so that scanning modulation will be the only limitation. For simplicity, it will be assumed here that the rest of the system is to be designed for 40-db cancellation ratio, which is a voltage cancellation ratio of 100 to 1.

Limit on Phase Instabilities

Since moving targets are detected as doppler frequency variations in the phase detector output, then anything that causes the phase detector output to vary from pulse to pulse will be interpreted as a moving target. In order to obtain 40-db cancellation ratio for strong fixed targets, instabilities must not cause the phase detector output to vary by more than 0.01 of full output, as shown in Figure 6. At the point of maximum phase detector sensitivity to small changes, an output of 0.01 of maximum will be caused by a 0.01 radian change in phase, or 0.57 degree.

Frequency Domain Interpretation

It is interesting to study the MTI stability problem in the frequency domain also. The spectrum of a pulsed transmitter is shown in Figure 7; it is a line spectrum, the lines being spaced by the pulse repetition rate. The echo from a fixed target will be exactly the same, but the echo from a moving target will be very slightly shifted in frequency by the doppler effect. The MTI system must detect the moving target in the presence of a strong fixed target, as shown in Figure 8. Anything that will cause fixed targets alone to have this same spectrum picture will deceive the receiver into thinking a moving target is also present. If the transmitter or receiver introduces frequency or phase modulation in the signal path, sidebands will appear around each spectrum line. The amplitude of these sidebands are, for small moduation index, just equal to half the modulation index. The modulation index

for frequency modulation or phase modulation is given by $m=\Delta f/f_m=\Delta\phi$, where Δf is the frequency deviation, f_m is the modulation frequency, and $\Delta\phi$ is peak phase modulation. The phase detector will respond to both the upper and lower sidebands, so that to obtain a residue 40 db below full output, the pairs of sidebands must be no greater than a 40-db weaker moving target, or 0.01 as strong as the main spectrum lines of the fixed target. Since $m=\Delta\phi$, this again results in the requirement that accidental phase modulation in the transmitter or receiver be no greater than 0.01 radian.

Limit on AM

Amplitude modulation of one percent could also produce a one percent variation in phase detector output and would limit the cancellation ratio to 40 db. In practice, however, by the time various other stability requirements are met, the AM is usually very small anyway.

Limit on Transmitter FM

In the case of a pulsed oscillator transmitter, the AFC system insures that the Stalo will follow changes in the transmitter frequency, but only on the average. Slow variations in transmitter frequency due to temperature drift, for example, will be followed by the Stalo, but rapid variations in frequency from pulse to pulse such as would be caused by modulator ripple will not be followed. As a result, when the echo pulse is received, the slight difference in frequency will cause the output of the phase detector to vary during the echo pulse length, as the received phase angle gradually gets ahead of or behind the phase angle of the Coho, as shown in Figure 9. The Coho is phase-locked according to the transmitter output on each pulse, but after the transmitted pulse is over the Coho runs at its own fixed resonant frequency. Since the Coho was last locked to the tail end of the pulse, there will be no error at the tail, but the leading edges of consecutive pulses will be off by the phase angle resulting from any pulse-to-pulse transmitter frequency difference times the pulse length; and averaged over the pulse length this is equivalent to a fixed phase error of half this much. Thus, for 40 db cancellation ratio, the transmitted frequency of the pulsed oscillator must be steady within $0.01/\pi\tau$ cycles per second, where τ is the pulse length. For a 2-microsecond pulse

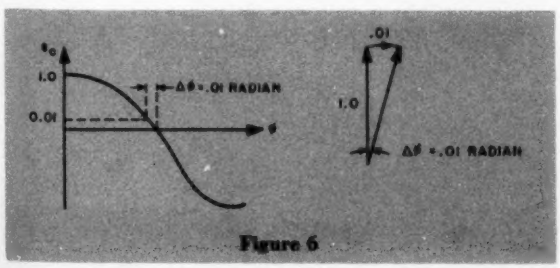


Figure 6

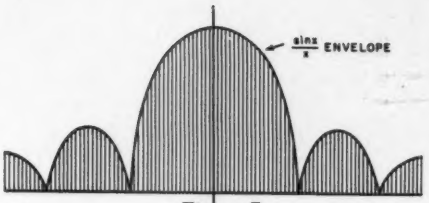


Figure 7

this would require the pulsed oscillator frequency to be stable within 1.6 kc at the carrier frequency of 1300 megacycles. This is a short term stability of 1 part in 10^6, which requires excellent filtering of modulator power supply ripple.

In practice, the bandwidth of the phase detector is usually tailored to the pulse length, and steep waveforms as shown do not appear; however, the amplitude of the actual rounded waveforms will correspond to the average amplitudes of the theoretical pulses shown here.

Stalo & Coho FM

If the Stalo frequency changes from one pulse interval to the next, the change in frequency will cause a phase error equal to the phase error per cycle times the number of cycles between the transmitted pulse and the echo return. This phase "runout" must be limited to 0.01 radian to permit 40-db cancellation ratio, and if MTI is to be used out to 50-mile range, this requires the Stalo to be stable within an FM deviation of 3 cps. At 1300 megacycles, this is a required stability of 2.3 parts in 10^9 that must be held during the time on target. This extremely high stability in a tunable oscillator requires great care in mechanical and electrical design.

It is interesting to note that the frequency stability requirement on the Stalo is much more severe than the requirement on the transmitter. This difference occurs because phase error due to transmitter frequency error only accumulates for one pulse length, while in the case of the Stalo it accumulates for the whole time it takes to receive echoes from targets 50 miles away. As noted in connection with Figure 1, the transmitter produces pulses so that the time to receive echoes can be measured, but the time delay is measured in terms of cycles of the reference oscillator.

The Coho must also be stable within 3 cps, but at the lower frequency of the Coho the design problem is not as difficult. However, care must be taken that the Coho be locked during each transmitted pulse within an accuracy of 0.01 radian to permit 40 db cancellation ratio.

Intrapulse Phase Variations

Variations in phase may also take place during the pulse length. Since the bandwidth of the receiver is tailored to the pulse length, the phase detector output

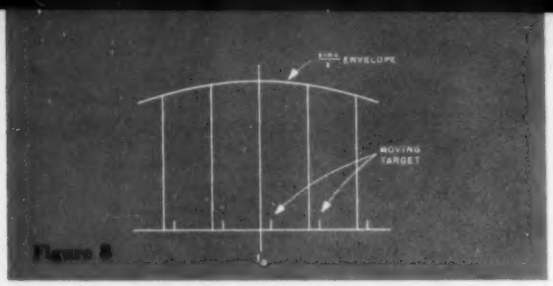


Figure 8

will be the average of what it would be if it could follow the variations. If these variations are large, the maximum output available from the phase detector will be reduced, as shown in Figure 10. This will cause a loss in system sensitivity and should be minimized by keeping the intrapulse phase variation below 1 radian. If the intrapulse phase variation is a linear change during the pulse length, then it is equivalent to a shift in transmitted frequency of $\Delta\phi/2\pi\tau$ cycles per second, where $\Delta\phi$ is expressed in radians; that is, a slightly mistuned Stalo in a pulsed oscillator system will also cause a loss of sensitivity by causing a phase change during the received pulse length. Even if the Stalo is exactly tuned according to the average pulsed oscillator frequency, a large enough frequency change during the transmitted pulse can again cause loss of sensitivity. If the transmitter frequency change is linear during the pulse, the resulting phase change will be parabolic; in any case, the total phase change, also called phase runout, should be held to approximately one radian or less. This can be expressed approximately as $2\pi\ \Delta f\ \tau < 1$, where Δf is now the intrapulse frequency change.

Time Jitter

Time jitter in an MTI system must also be held within tight limits. The canceller that follows the phase detector will only cancel signals that do not vary in amplitude or in time of appearance. A delay line canceller works by storing the phase detector video output signals from one pulse and subtracting them from those of the next pulse; and if the second pulse is a little late, as shown in Figure 11, two spikes will be left over. Actually, the bandwidth of the canceller is tailored to the pulse length, so that the canceller output will not build up to full amplitude in such a small fraction of a pulse width; it is more likely, in fact, to be *headed* toward full output in about one pulse length, so that the voltage amplitude that does build up will be proportional to the amount of pulse misalignment. The uncancelled residue that will result, therefore, will be equal to the time jitter divided by the pulse width. A factor of two should probably be included to cover the fact that there is misalignment at both the beginning and end of the pulse. This means, for example, that time jitter in the firing time of the ARSR-1A modulator and pulsed transmitter must be held constant within 0.01 microsecond in order to permit 40 db cancellation ratio.

Summary of Instability Limits

The limits on instabilities that affect MTI cancellation ratio are summarized below. The successful design of the ARSR-1A coherent MTI system is the result of careful attention to all these factors.

Instability limits for 40 db cancellation ratio:

Pulsed oscillator transmitter FM:	$\pi\Delta f\tau < 0.01$
Amplifier phase modulation in transmitter or receiver:	$\Delta\phi < 0.01$
Time Jitter:	$2\Delta t/\tau < 0.01$
Stalo or Coho FM (for MTI to 50 miles):	$3.4 \times 10^{-3}\Delta f < 0.01$
Coho phase locking error:	$\Delta\phi < 0.01$

Other limits to avoid loss of sensitivity

Pulsed oscillator transmitter intrapulse FM:	$2\pi\Delta f\tau < 1.0$
Amplifier intrapulse phase modulation in transmitter or receiver:	$\Delta\phi < 1.0$
Stalo or Coho detuning:	$2\pi\Delta f\tau < 1.0$

Conclusion

The usefulness of a radar system whose primary function is the detection and tracking of aircraft in the presence of strong ground clutter is significantly improved by the use of MTI techniques. As is usually the case, we must pay a price for this improvement. Although the system concept is relatively simple, its implementation requires considerable care in controlling factors that are not of significance in a non-MTI radar. It has been the intent of this article to describe basically how conventional MTI systems work and to indicate limits on various instabilities that must be controlled to make an MTI system work well.

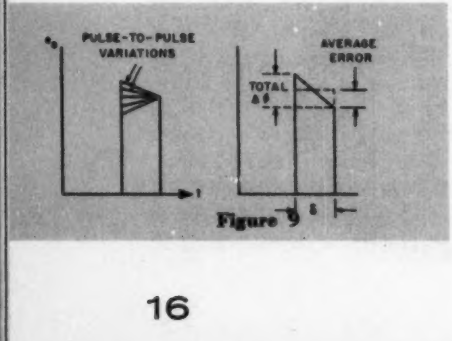


Figure 9

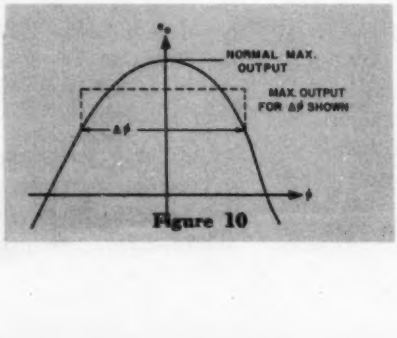


Figure 10

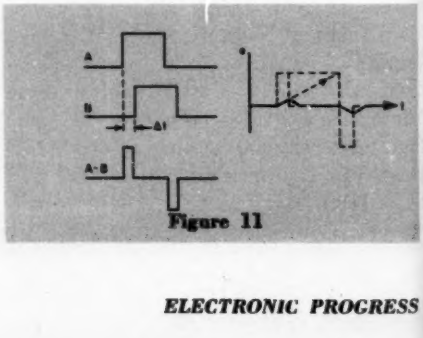


Figure 11

PYROGRAPHITE

S. L. Blum, J. Pappis **Research Division**

DEVELOPMENT of a new process at the Research Division has produced a synthetic material which very closely approximates the single crystal form of natural graphite, a valuable but unfortunately rare substance. This material, Pyrographite, promises to solve many critical military problems in the high-temperature area, as well as offering unusual opportunities for fundamental research.

Natural graphite, the flaky, slippery form of carbon, is found in various rock formations throughout the world. Very small and purified crystals have been obtained and used to study various properties of the basic graphite structure. A significant result of this work was the demonstration that properties of single crystal graphite differ significantly with direction. This difference in properties (termed anisotropy, in contrast to isotropy which indicates identical properties in all dimensions) arises from the variations in chemical bonding in the different crystallographic directions, and can be quite important. Electrical conductives, for instance, are from 100 to 1000 times greater along the length than through the thickness, while thermal conductivities are at least 10 times greater lengthwise. This anistropy is appealing because of its possible application to many fields, but the smallness and rarity of single crystals of graphite has not permitted their use.

Commercial graphite, the more familiar form, is a ceramic product which is usually made by mixing a petroleum coke flour with a coal tar pitch binder. The mixture is extruded or molded to desired shape and then baked at temperatures of about 1000°C and heat treated in the range of 2500 to 3000°C. This graphite has a fairly low density (1.6 to 1.7 gm/cc); it is hard compared to natural graphite flakes; it is strong and, in fact, is the strongest material known at temperatures above 1500°C. It is of course the commercial form of graphite that is used in electric furnace electrodes, crucibles, motor brushes, furnace elements, foundry facings, and similar products. On the debit side, one finds that commercial graphite is porous to gases; it has variable properties from piece to piece and also within a piece because of the nature of the process used to make it.

It had been known for some time (approximately 50 years) that it was also possible to deposit a form of graphite from a carbonaceous gas at very high temperatures. This material, however, had little practical value because it could not be made into large, convenient shapes due to the techniques for deposition. It essentially remained a laboratory curiosity until the Research Division scientists started to work with it and developed the first commercially feasible fabrication process. The material was named Pyrographite because it was deposited using the technique of pyrolizing or decomposing carbon-bearing gases.

Pyrographite was originally prepared at Raytheon as an impervious coating for core elements in connection with a proposed atomic reactor. In addition to being impervious to helium and stronger than commercial graphite, Pyrographite was found to exhibit a high degree of anistropy, similar to that of natural graphite single crystals. This unique property led to considerable further study of the material.

The strongest interest in Pyrographite presently is for missile application because of high thermal conductivity lengthwise and insulating properties in its thickness direction, its strength to weight ratio, and its refractoriness. It has been used to date for re-entry heat sink bodies and rocket liners. It has been tested in various arc jets and rocket motors and is considered the most promising material at present for some of the country's most important missile programs. There has also been an interest in Pyrographite for furnaces, crucibles, high-temperature bearings, and lubricating material. The same degree of anisotropy shown in thermal properties is evidenced in electrical properties, and its application in the electronic industry is now under careful study.

Figure 3

Structure

The fibrous microstructure of Pyrographite is typical for vapor-deposited materials. Figures 1 and 2 are photomicrographs which show cross sections of plate material. It can be seen that the fiber structure varies with the conditions of deposition.

There are several ways in which the three types of graphite differ in structure. Natural graphite is made up of flat, hexagonal cells stacked one on top of the other, as in Figure 3. The hexagons are in the basal plane and these planes are 3.35 Angstroms apart. The nearest atoms within the plane are only 1.42 Angstroms apart. In natural graphite, alternate planes line up, with the in-between planes displaced slightly. In Pyrographite, there is no such order. This can be visualized in terms of the model in Figure 4. Here short cylinders have been used instead of hexagonal cells. The line, however, represents an atom at one corner of the hexagon. Single crystal graphite is shown with the lines (atoms) having a consistent relation to one another. Pyrographite is shown with the lines at random positions. The atoms within a plane are exactly the same distance apart in both forms; however, the natural graphite has less space between planes. That is, since the stacking is random, the atoms do not seem to fit together as well, and the Pyrographite has a distance of from 3.40 to 3.45 Angstroms between planes as compared to 3.35 Angstroms for single crystals of graphite. For high density Pyrographite, this spacing approaches 3.35 Angstroms.

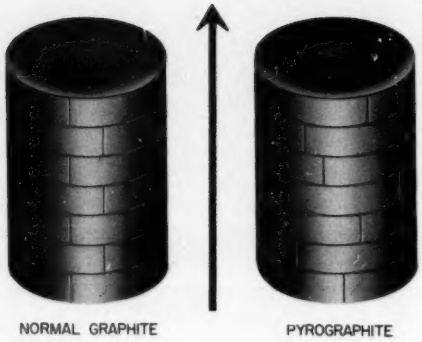


Figure 4

There is another difference in the manner in which groups of cells, or crystallites, are put together. While commercial graphite is just a large number of small graphite crystallites held together randomly with a tar pitch binder, Pyrographite, on the other hand, shows an unusually high degree of preferred orientation on the macroscopic scale. Its crystallites tend to have their basal planes aligned parallel to the surface of the sample. A more quantitative description of the preferred orientation is best understood with the aid of the model shown in Figure 5. Imagine that a flat sample is placed in the center of a sphere and that the orientation of each crystallite composing that sample

TABLE I

PROPERTIES OF VARIOUS MATERIALS

at Room Temperature

Property	Pyrographite	Graphite	Alumina (Al_2O_3)	Copper	Tungsten
Sublimation or Melting Point (°C)	3652-97	3652-97	2035 ± 10	1083	3370
Boiling Point (°C)	4200	4200	3500	2336	5900
Density (gm/cm^3)	1.80-2.22	1.6-2.0	3.98	8.92	19.3
Tensile Strength (psi)	15-20,000	2-4,000	30,000	60-70,000	120,000
Specific Heat (cal/gm/°C)	0.232	0.17	0.184	0.0921	0.034
Thermal Conductivity (watts/cm^2/°C/cm)	a—1.6-3.9 c—0.02-0.035*	1.89	0.30	3.89	1.99-1.47
Spectral Emissivity	0.81-0.90	- - -	0.22-0.90	0.10	0.43
Electrical Resistivity (Ohm-cm)	a—200-250 x 10^{-6} c—0.25	800 x 10^{-6}	10^{14}-10^{18}	1.77 x 10^{-6}	5.51 x 10^{-6}
Thermal Expansion (deg^{-1})	a—2.1 x 10^{-6} c—24.8 x 10^{-6}	7.86 x 10^{-6}	- - -	16.8 x 10^{-6}	4.3 x 10^{-6}
Strength / Density (approximate)	10 x 10^3	1.34 x 10^3	7.55 x 10^3	7.3 x 10^3	6.2 x 10^3
At 2700°C	30 x 10^3	200	25	- - -	250

*Absolute value depends on density.

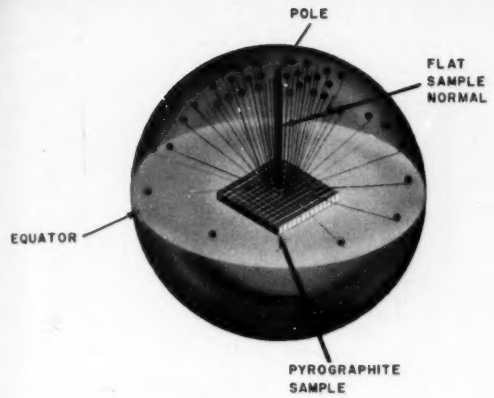
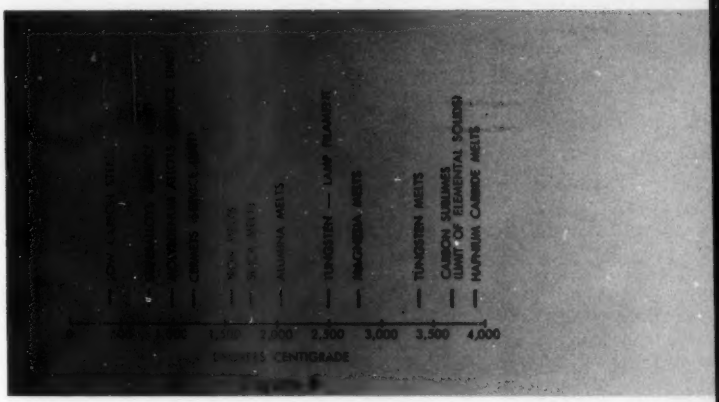


Figure 5



is indicated by a normal to its basal planes. Wherever this normal penetrates the surface of the sphere, we mark a point. In order to relate the crystallite orientations to that of the sample itself, we also mark the penetration point of the sample normal and call it the pole. Since there are a large number of crystallites, the surface of the sphere will be covered with points and their distribution can be described by point density. For a sample with random crystallite orientation, the point density on the surface would be constant. For a sample with some preferred orientation, the point density will be heaviest in the direction of orientation. Note that this is exactly the case for Pyrographite.

Properties

From the foregoing description of structure, it is to be expected that Pyrographite will have significantly different properties than commercial graphite. The best Pyrographite should actually approach single crystal natural graphite in its properties. Table I compares Pyrographite with commercial graphite and with a number of other materials. Most interesting are the anisotropic, the thermal, electrical and mechanical properties.

Thermal

Graphite, which sublimes at 3652-3697°C, has the highest temperature limit of any elemental material (see Figure 6), making it particularly suitable for high temperature applications. Pyrographite, due to its ordered layer structure, combines a high temperature limit with a high degree of anisotropy of heat transfer characteristics. Figure 7 shows the thermal conductivity of Pyrographite compared with various other materials. It can be seen that in the "a" direction, Pyrographite has a higher heat conductivity than copper, while in the "c" direction, it is lower than normal graphite.

It is interesting to compare the thermal conductivity of Pyrographite in the "c" direction with that of ceramic insulators, as is done in Figure 8. Note that in the temperature range measured, the ceramics tend to increase in thermal conductivity at elevated temperatures, whereas the high density form of Pyrographite decreases. This increase in thermal conductivity of ceramic materials above some characteristic temperature (1200°C) is quite common and is associated with a radiation contribution to thermal conductivity. No such contribution has been shown to date for graphites. For Pyrographite, the characteristic increase in thermal conductivity may show up at very much higher temperatures. In any case, the high temperature insulating properties of Pyrographite compare favorably with conventional solid thermal insulators. This conclusion has been verified by very high temperature arc plasma and rocket motor tests.

Mechanical

Limited measurements of Pyrographite mechanical properties have been made. The most significant of these noted to date are strength and erosion resistance. Tensile strength measurements at room temperature show a value of 20,000 psi. Various other measurements at high temperatures have been made, with

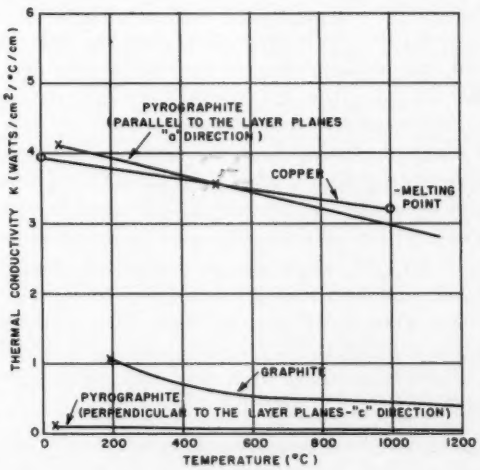


Figure 7

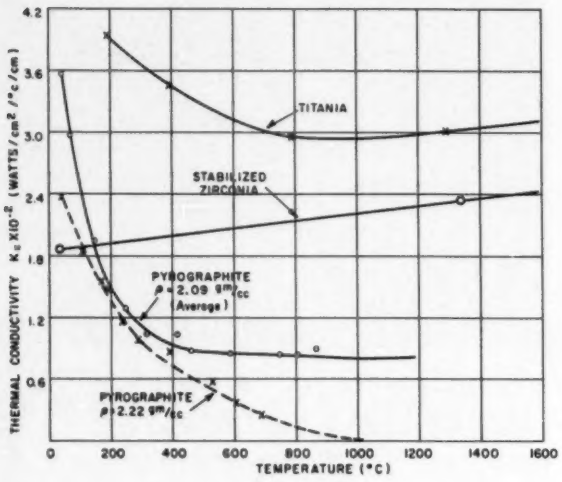


Figure 8

values in the neighborhood of 60,000 psi at temperatures approaching 2750°C. A comparison of the strength of Pyrographite with several other high temperature materials is shown in Figure 9.

The shear strength, as would be expected from the structure, is not high, but there is some feeling that adding impurities to the graphite will increase this strength. An impurity will act as a "key" to keep the planes from sliding over each other, much as the potassium atom does for mica. That is, the impurity atom will sit between two basal planes and be loosely bound to atoms in both planes. This binding will help keep the planes from slipping under an applied shear force.

Various rocket firing tests have been conducted with Pyrographite and normal graphite in highly erosive atmospheres with high velocity, high temperature reducing streams of solids and gases. Pyrographite has shown little erosion under conditions where graphite breaks down completely. This property, like many others, can be attributed to the high degree of order in the crystal lattice which causes low-reactivity basal planes to be presented to the gas stream.

Normal commercial graphite oxidizes readily above 600°C. Pyrographite does not oxidize as fast as ordinary graphite at lower temperatures but above 1500°C oxidizes at about the same date. As shown in Figure 10, the oxidation rate constant for Pyrographite increases slowly below 875°C but rises very rapidly between 875 and 1470°C. This property in addition to mechanical strength makes Pyrographite a desirable material for high temperature bearings and possibly for lubrication at least up to 1500°C.

Impermeability

Of particular interest for applications in nuclear

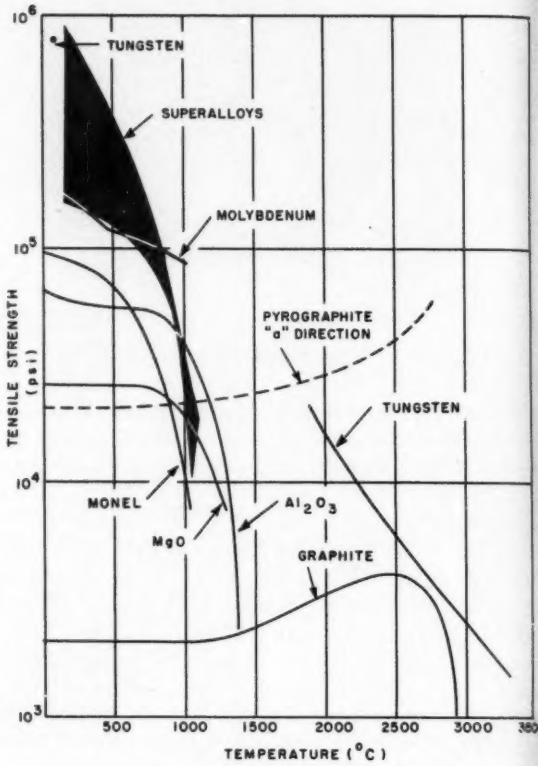


Figure 9

reactors is the impermeability to gases which Pyrographite demonstrates. At pressures below 10^{-6} mm, absolutely no permeation by helium, one of the most penetrating of gases, has been detected. The material continues to exhibit this property after heating to 2500°C and re-cooling, and in films as thin as 1-2 mils. It also has been found that Pyrographite is rather easy to outgas in a vacuum system.

Electrical

A number of experiments measuring the electrical properties of Pyrographite are being conducted. In most cases complete data are not yet available, but initial results show anisotropy with regard to electrical conductivity similar to that noted with thermal conductivity. The resistivity in the "c" direction increases with higher preparation temperatures, while in the "a" direction it decreases. The degree of anisotropy is of the order of 1000 to 1 for material prepared at 2000°C. As indicated in Table I, the resistivity along the layer planes is considerably less than that of the normal graphite, which is considered a good conductor; across the layers it is far greater than graphite.

At microwave frequencies, X- and L-band, the same anisotropy in conductivity is found. The resistivity is found to be independent of frequency.

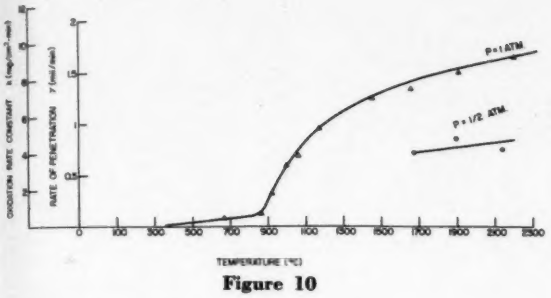


Figure 10

Related Materials

There is experimental evidence that by introducing various non-carbonaceous materials into the Pyrographite process, it is possible to produce a wide range of related materials, the applications of which could be even more important than those of Pyrographite. Little data has yet been developed but materials under study include:

1. Pyrographalloys — These are alloys of pyrographite with various metals. Through metal selection, it is possible to tailor-make strength, thermal, and reactivity characteristics.
2. Pyrocarbides — These are compounds of various metals with Pyrographite. These compounds can be produced with a wide range of special properties including high wear-resistance and extremely high temperature limits.
3. Pyrofibers — These are Pyrographite fibers which can be used for thermal insulation, and for strengthening of plastic and Pyrographite shapes. Through orientation of reinforcing fibers it is possible to vary thermal characteristics.

The development of this new material has already aroused interest among both military and commercial groups. It is believed that within Raytheon itself, Pyrographite and all its related materials present many opportunities for improvement of existing parts. A pilot plant is now in operation in Lawrence, Massachusetts for the production of large quantities of Pyrographite of many shapes and uses. Members of the high-temperature materials group of the Research Division are presently engaged in studying various possible uses and would be quite interested in any ideas that others may have in these directions.

Publications & Papers

W. C. BROWN, "Practical Utilization of Power Transmission by Electromagnetic Beams for Propulsion Purposes," presented at the PGMTT Meeting in New York on March 3, 1960.

The crossed-field microwave device has traditionally been a power device and, in its magnetron oscillator form, was responsible for the early growth of high power microwave radar. The qualities of high efficiency, simple construction, and power handling capability found in the magnetron oscillator have been preserved in the continuous-cathode crossed-field Amplitron device which also possesses the desirable characteristic of broadband amplification. The extension of the Amplitron into the super-power area by combining the high efficiency of the device with new cooling techniques for handling high dissipation densities is discussed. Other features of these power tubes which are reviewed include nearly constant efficiency over electronic bandwidths of 6-12 per cent, low-phase pushing, excellent phase linearity, low X-ray generation, and compact and economical packaged construction.

J. J. GREEN, U. MILANO, E. SCHLOMANN, "Recent Developments in Ferromagnetic Resonance at High Power Levels," published in the JOURNAL OF APPLIED PHYSICS, April 1960.

The influence of inhomogeneities on the saturation of the ferromagnetic resonance is investigated. In the region of moderate power levels the susceptibility at resonance χ'' varies linearly with the square of the rf field h. The magnitude of the slope $\partial\chi''/\partial h^2$ depends on the nature of the dominant scattering mechanism.

At very high power levels the opening angle of the precessing magnetization vector approaches a limiting value, which is related to the "linewidth" ΔH_k of z-directed spin waves having the same frequency as the uniform mode. Experiments on single crystals and polycrystals of rare-earth-substituted garnets show that ΔH_k increases approximately linearly with the rare earth content. The materials investigated contain Gd, Yb, Er, Sm, Dy, Ho, or Tb and, for a given ratio of substitution, ΔH_k increases in that order.

A new nonlinear effect arising from spin-wave instability in a microwave magnetic field applied parallel to the dc field has been observed. The observed variation of the critical rf field strength agrees well with the theoretical predictions. It indicates that the spin-wave line width increases with increasing wave number and decreasing angle between propagation direction and dc magnetic field.

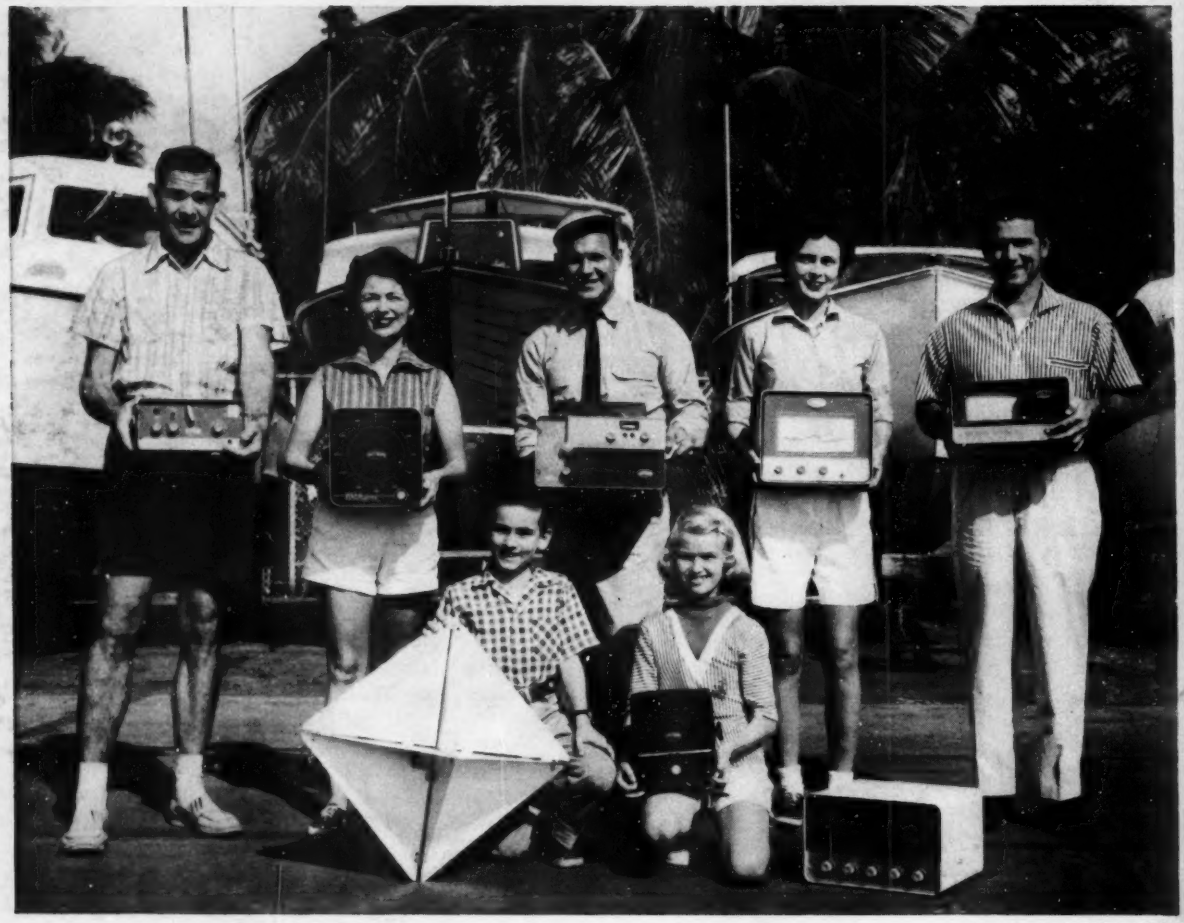
D. L. McMURTRIE, "Magnetic Amplifier Circuits," published in COMMUNICATIONS AND ELECTRONICS, January 1960.

The magnetic amplifier literature presents a varied and rather confusing array of magnetic amplifier circuits. The present article shows that much of the confusion is unnecessary. Specifically, we develop a simple, orderly classification of self-saturating magnetic amplifier output circuits. Important constraints exist which make it possible to evaluate output circuits independently of control arrangements. Once a degree of order has been established for output circuits, the study of control circuits is greatly simplified. It is possible, for example, to analyze and arrange control circuits applicable not just to single output circuits but to classes of equivalent output circuits. These control arrangements are not dealt with in the present article.

The familiar half-wave (HW) circuit, the simplest form of self-saturating circuit, is used as a basic building block with which to construct the more complex reversible half-wave (RHW), full-wave (FW), and reversible full-wave (RFW) output circuits. (We add ac or dc to the above designations to indicate alternating or direct output.) The technique is a straightforward one for deriving even the most complex circuits, and allows a means of rapid search for equivalent or improved circuits. It is an unpleasant fact that serious interactions often occur when HW circuits are combined to form more complex structures. The present article measures and classifies these interactions.

E. MILLER, W. F. RICHARDSON, N. SEROTTA, "The Measurement of River Flow by use of Underwater Sound," presented at the PGUE Session of the IRE Convention in New York on March 24, 1960.

A survey of presently known methods of measuring river flow is presented. The results of a study of the use of acoustic signals for the determination of flow velocity are given. Several different acoustic flowmeter systems are evaluated.



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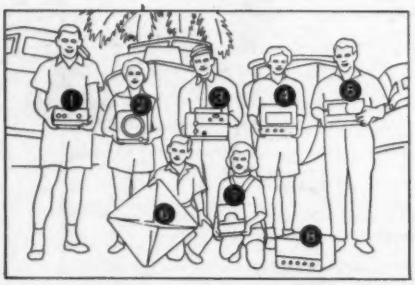

1. Model RAY 11 radiotelephone, $259.50. 2. Fathometer® depth sounder Model DE-706, $385. 3. "Ranger" radio direction finder, $299.50. 4. Fathometer Model DE-707, $575 (new this year). 5. "Explorer" Model DE-705, $255. 6. Radar reflector, $14.95. 7. "Holiday" depth sounder, $159.50. 8. Model RAY 23 radiotelephone, $385.50. (Suggested prices — subject to change.)

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